

Determining Greenland Ice Sheet Accumulation Rates from Radar Remote Sensing

Final Project Report

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Table of Contents

1	Introduction	2
2	Summary of Results	2
2.1	Measurements of Surface Backscatter on the Greenland Ice Sheet	2
2.2	Estimating a Volumetric Backscatter Coefficient from in-situ data	4
2.3	Basal Topography around the Jakobshavn Glacier	4
2.4	Seasonal melt characteristics on the Greenland ice sheet	7
2.5	Determining Accumulation Rate from Spaceborne Radar	9
3	Contributions to PARCA	12
3.1	Cumulative Presentations and Publications	12
3.2	Thesis and Dissertations	14
4	References	15

1 Introduction

An important component of NASA's Program for Arctic Regional Climate Assessment (PARCA) is a mass balance investigation of the Greenland Ice Sheet. The mass balance is calculated by taking the difference between the snow accumulation and the ice discharge of the ice sheet. Uncertainties in this calculation include the snow accumulation rate, which has traditionally been determined by interpolating data from ice core samples taken throughout the ice sheet. The sparse data associated with ice cores, coupled with the high spatial and temporal resolution provided by remote sensing, have motivated scientists to investigate relationships between accumulation rate and microwave observations.

2 Summary of Results

The goals of our project have been to exploit high resolution space-borne radar data to: 1) estimate the seasonal and inter-annual variations in accumulation rate across the Greenland Ice Sheet; 2) understand causal mechanisms behind accumulation rate patterns; 3) contribute to other ice sheet studies that are part of the Program of Arctic Regional Climate Assessment. Our focus has been to develop inversion techniques for relating radar backscatter to accumulation rate using our forward model, which combines a snow metamorphosis component with radiative transfer theory.

2.1 Measurements of Surface Backscatter on the Greenland Ice Sheet

We base our work on a solid understanding of microwave backscatter from firm derived from a series of *in-situ* measurements. We conducted *in-situ* measurements from 1991-1995. Measurement included observation of backscatter from 0.5-18 GHz with the angle of incidence varied in 5° increments from 0° to 50° from the surface normal. Backscatter plots from NASA-U and GITS are shown in figures 2 and 3, respectively. The relative flatness of the curves beyond about 25° is indicative of volume scatter. This observation is exploited in our accumulation rate algorithm.

We have refined our processing techniques to include corrections for antenna pattern and range dependent loss mechanisms. A schematic of our ground based radar system is shown in figure 1. Using these refined techniques we have made significant progress has been made in relating spaceborne to *in-situ* data. Discrepancies between spaceborne radar and *in-situ* data result from an additional spreading term, which is present in the ground-based data. Differences between *in-situ* and spaceborne derived backscatter are shown in figure 4, as a function of range to snow, R_s , for various extinction coefficients. Graphs of this sort can be used to back out the extinction coefficient when there are coincident surface and spaceborne scattering experiments. We are in the process of finalizing results from this study, which will be submitted for publication in *IEEE Transactions on Geoscience and Remote Sensing*.

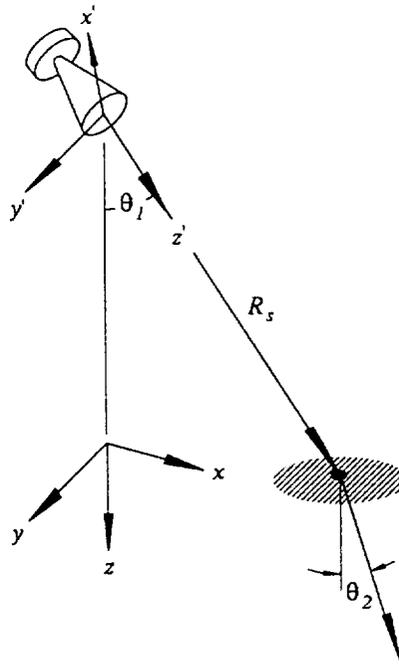


Figure 1: Schematic of *in-situ* antenna illuminating snow surface. The shaded region corresponds to the main antenna beam.

2.2 Estimating a Volumetric Backscatter Coefficient from *in-situ* data

Using *in-situ* data from the dry-snow zone, we developed a method for estimating the volumetric backscatter coefficient as a function of depth in firm. Results show trends consistent with both seasonal variations and long-term grain growth, which is primarily influenced by the accumulation rate. The results further suggest that, at large incidence angles, radiative transfer algorithms based on volume scattering provide a reasonable model for firm scattering within the dry-snow zone. Figure 5 shows the correlation between volumetric backscatter and $\delta^{18}\text{O}$, which is related to seasonal variations in grain size.

2.3 Basal Topography around the Jakobshavn Glacier

As part of OSU's study of Jakobshavn Glacier [Sohn *et. al.*, 1998], we requested a series of AOL and radar flights across the ice stream. The objective of the flights was to provide new information on the sub glacial topography, surface topography and driving stress on the ice sheet in and around the ice stream. In figure 6, we present a new map of basal topography which combines PARCA results with seismic data acquired over the ice stream [Clarke and Echelmeyer, 1989]. The seismic data were required because of the limited radar definition of the subglacial channel beneath the ice stream. The map shows that the glacier channel flows through a broader valley about 25 kilometers wide. There is a subtle indication of parallel broad valleys just to the south however; these do not seem to strongly influence glacier flow.

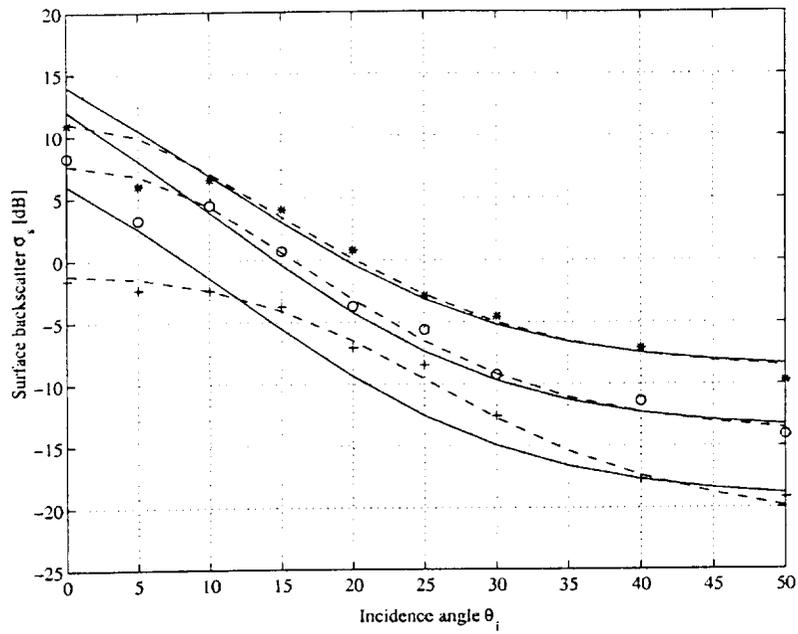


Figure 2: Backscatter at NASA-U site for 5.3 GHz (+), 10 GHz (o) and 13.5 (*) GHz. Solid lines the represent pencil beam approximation.

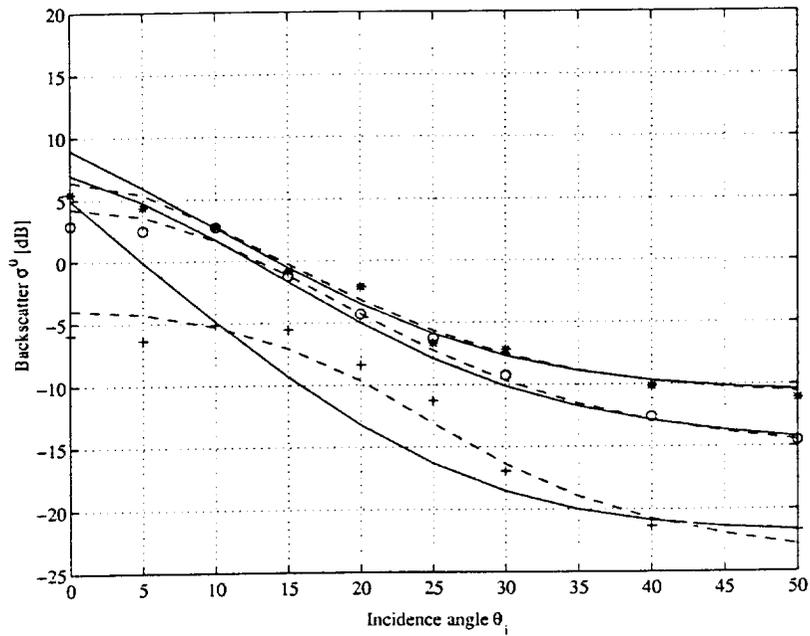


Figure 2: Backscatter at GITS site for 5.3 GHz (+), 10 GHz (o) and 13.5 (*) GHz. Solid lines the represent pencil beam approximation.

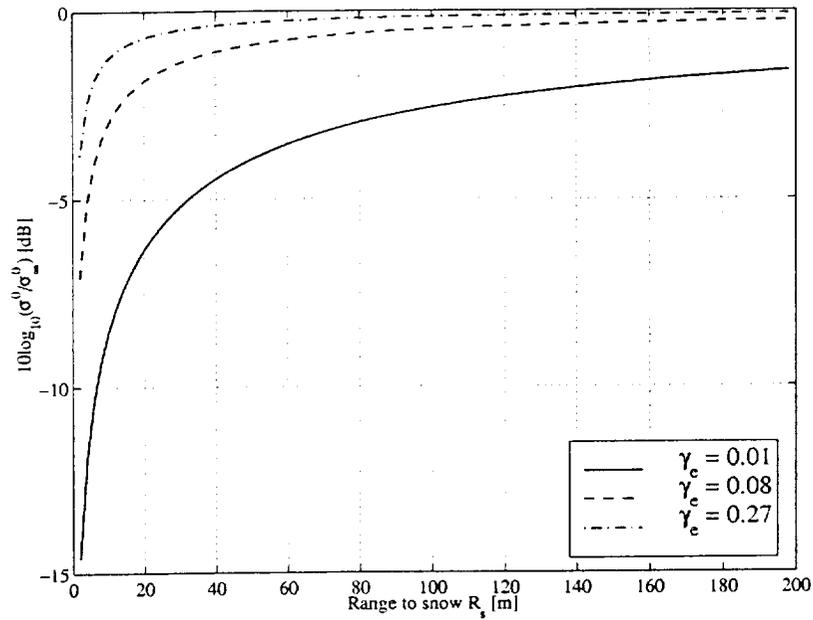


Figure 4: Ratio of *in-situ* to spaceborne radar backscatter, various extinction coefficients, γ_e .

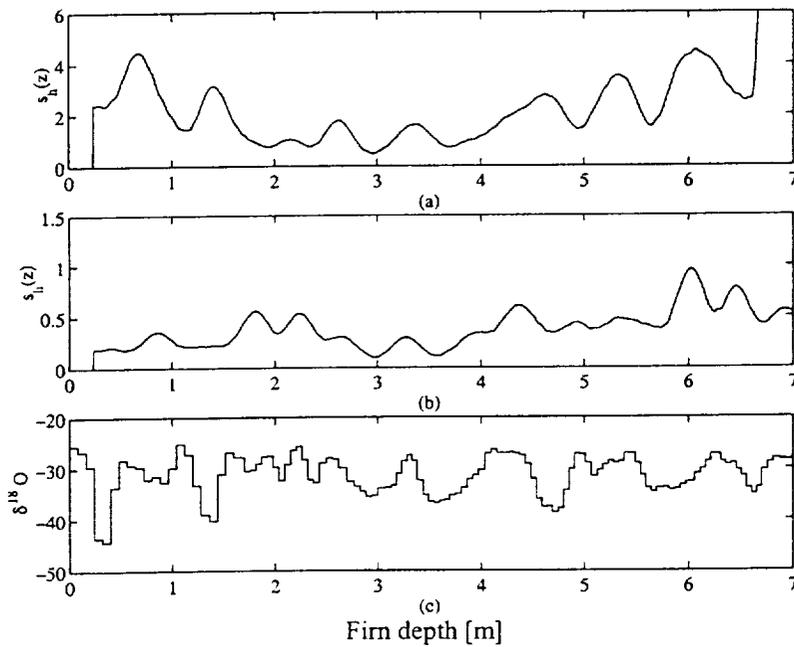


Figure 5: Plots from NASA-U site for, (a) $s_h(z)$ at 5.3 GHz ($\theta_1 = 50^\circ$) (b) $s_h(z)$ at 17 GHz ($\theta_1 = 50^\circ$) and (c) $\delta^{18}\text{O}(z)$. Note the similarities in shape between (b) and (c).

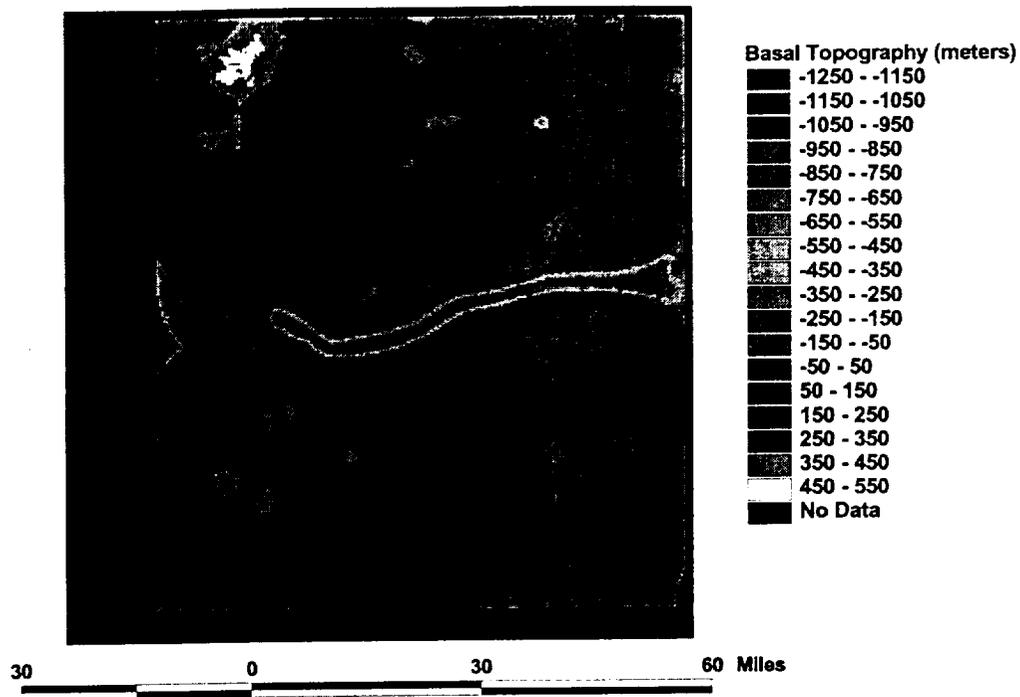


Figure 6: Basal topography near Jakobshavn Glacier (from *Lampkin*, [2000]).

2.4 Seasonal melt characteristics on the Greenland ice sheet

Passive microwave data from the DMSP SSMI and Nimbus 7 SMMR were used to estimate the annual extent of melt, the melt duration, and the length of the melt season on the Greenland Ice Sheet for the years, 1979-1997 [*Joshi*, 1999]. The approach involved application of an edge-detection algorithm to passive microwave time-series data. The new information on melt duration and length of melt season were better related to global temperature trends than melt extent alone (largely because of the ephemeral nature of melt along transitions zones between percolation and dry snow facies).

These observations led to two developments. First, better ability to interpret spaceborne imagery led to mapping the margins of the western Greenland Ice Sheet over time (see figure 7). Using a combination of techniques, Jakobshavn Glacier was shown to have systematically retreated over the past 150 years. As importantly the snout of the glacier was shown to have a seasonal behavior suggesting seasonal controls on the iceberg calving rate. Second, better understanding of microwave scattering from dry snow has led to the development of algorithms for extracting accumulation rate from passive microwave and SAR data [*Bolzan and Jezek*, 1999].

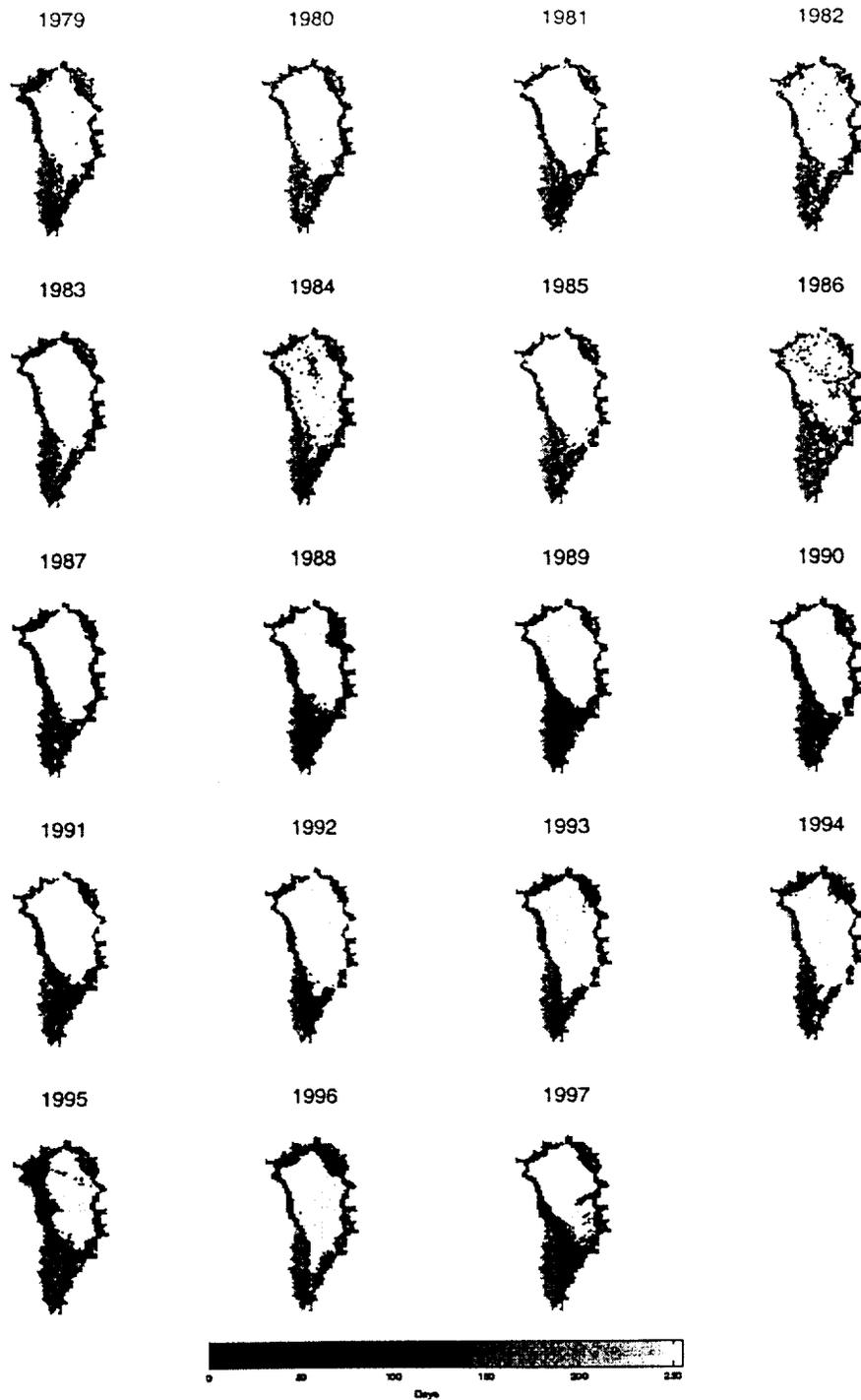


Figure 7: Maps of wet and dry areas on the Greenland ice sheet for the years 1979 through 1997 using the edge detection technique. The wet areas are shaded according to the duration of melt (from *Joshi*, [1999]).

2.5 Determining Accumulation Rate from Spaceborne Radar

The primary goal in our third year has been to quantify relationships for estimating accumulation rate, A_{sar} , from spaceborne SAR data. Using a combined snow-metamorphose and radiative-transfer model [Forster *et al.*, 1999] we generate a look-up table, which allows us to estimate accumulation rate based on radar backscatter and mean annual temperature within the Greenland dry-snow zone. The radiative transfer model used in our analysis is based on developments in the late 1970's by Chang *et al.*, [1976], Zwally, [1977] and Comiso *et al.*, [1981], in an attempt to better understand observed variations in microwave brightness temperature and radar backscatter over arctic regions. The model assumes that scattering is within the Rayleigh region, with coupling between individual snow grains neglected. Limitations on the grain size limit the validity of the model to the dry-snow zone, where no seasonal melting occurs and snow grains remain isolated in the upper firn. To account for coupling and a log normal distribution of grain size, an adjustment is made to the mean radius of the snow comprising the firn [Shi *et al.*, 1993].

Our accumulation map of the Greenland dry-snow zone is generated from the ERS-1 SAR mosaic of Greenland [Fahnestock *et al.*, 1993], with the mean annual temperature calculated using an expression derived by Reeh, [1989]. When compared to ice core derived accumulation, A_{ice} , our calculated rates differ by less than 20% over the entire dry-snow zone. Since the discrepancies are systematic, we feel that with improved calibration, average differences of less than 10% between A_{ice} and A_{sar} are achievable. Our derived accumulation rate map will be published in the special PARCA issue of {*Int JGR*}. A list of contributions resulting from PARCA research is given in section 3.

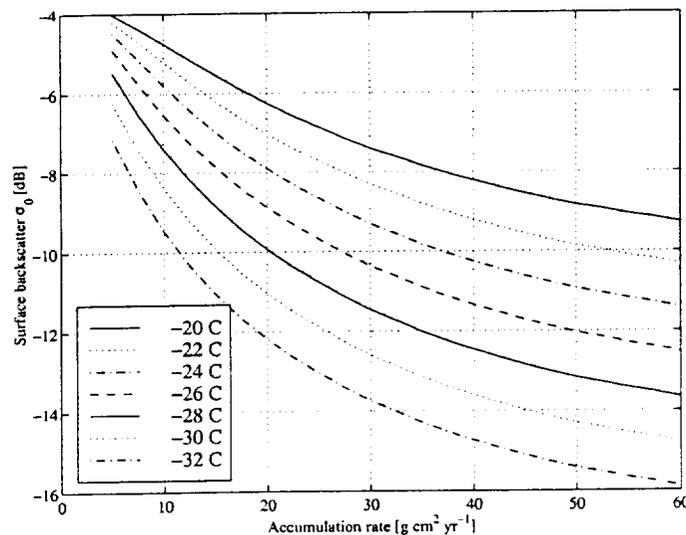


Figure 8: Backscatter, σ_0^0 , as a function of accumulation rate A over the temperature range $T_{avg} = -20$ to -33°C at C-band, calculated using the forward model.

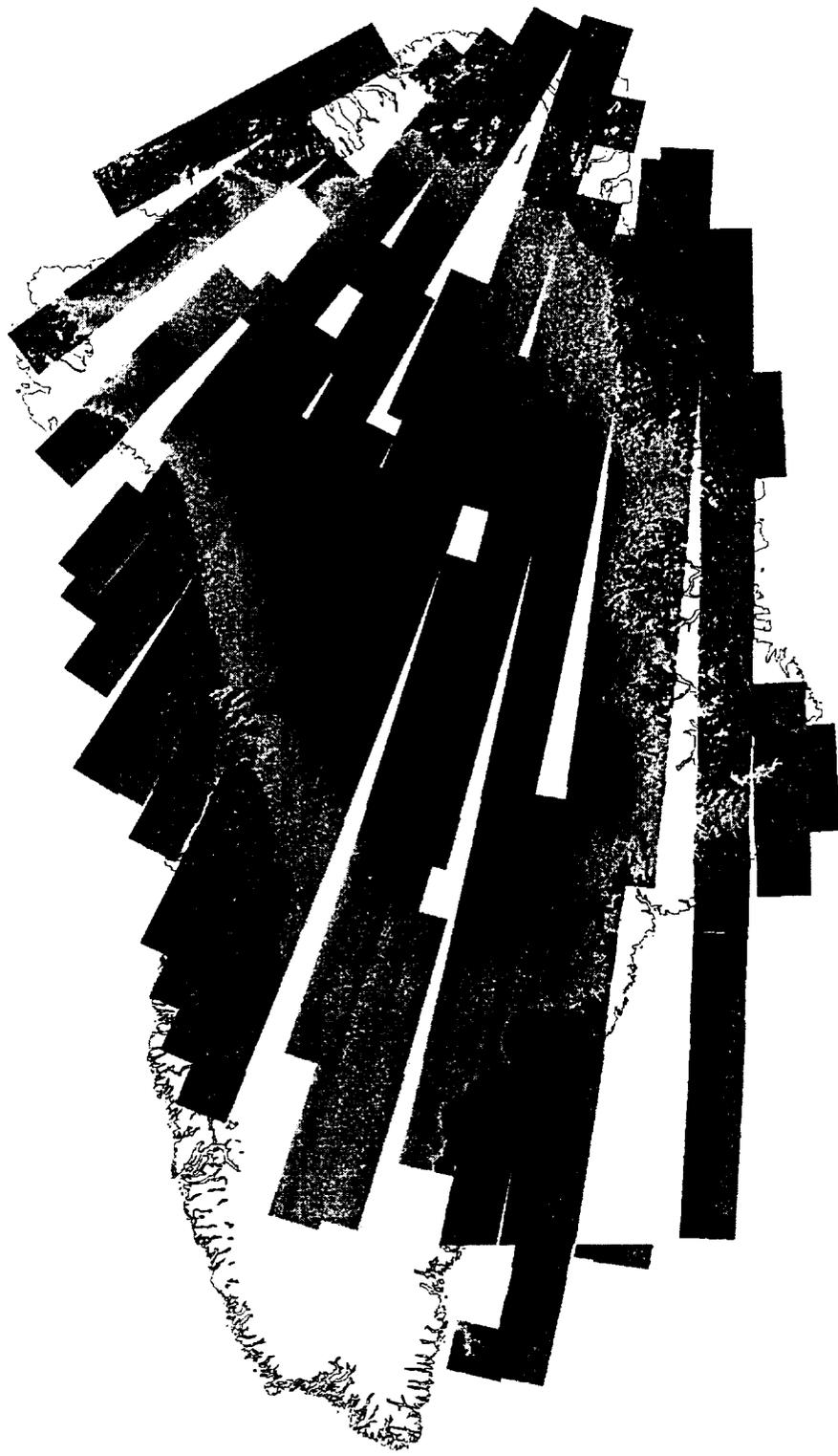


Figure 9: ERS-1 SAR mosaic compiled from data obtained during September-November, 1991 [*Fahnestock et. al., 1993*].

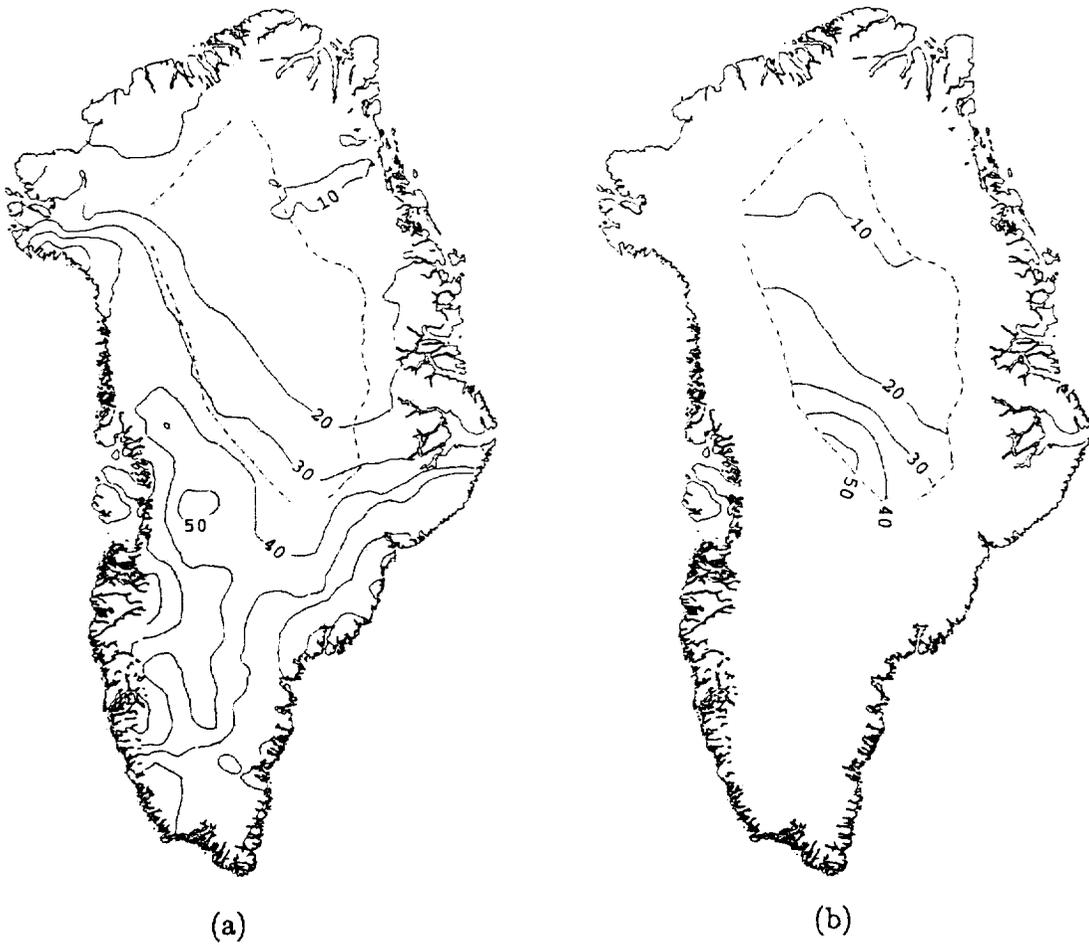


Figure 10: Comparison between; (a) Bales accumulation map; (b) present work. Contours are given in cm/yr w.e., with the dashed line corresponding approximately to the dry-snow zone.

3 Contributions to PARCA

3.1 Cumulative Presentations and Publications

- Baumgartner, F., K. Jezek, R. R. Forster, and S. P. Gogineni, 1998, "Ultra wide-band ground-truth radar data, Greenland, May 1995", Wallops Island, October, 1998.
- Baumgartner F., K. Jezek, R. R. Forster, S. P. Gogineni, and I. H. H. Zabel, 1998, "Spectral and angular ground-based radar backscatter measurements of Greenland snow facies", *IGARSS' 99*, Hamburg, Germany, 1052-1055.
- Bolzan, J. F, and K. C. Jezek, "Accumulation Rate Changes in Central Greenland from Passive Microwave Data", in revision *JGR -Oceans*.
- Forster, R. R., J. Bolzan, and K. Jezek, 1997, "Accumulation rate variability in Central Greenland from microwave remote sensing", Remote Sensing of Ices Workshop, Flagstaff AZ, June 1997.
- Forster, R. R., K. Jezek, I. H. H. Zabel, and S. P. Gogineni, 1997, "The relationship between microwave backscatter and glaciological properties of the Greenland glacier facies", AGU Fall Meeting, December, 1997.
- Forster, R. R., K. Jezek, J. Bolzan, F. Baumgartner, and S. P. Gogineni, 1999, "Relationships between radar backscatter and accumulation rates on the Greenland ice sheet", *International Journal of Remote Sensing*, **20**(15), 3131-3147.
- Jezek, K. C., 1993, "Spatial patterns in backscatter strength across the Greenland ice sheet", *Proceedings ERS-1 Symposium*, ESASP-359, 269-272.
- Jezek, K. C., M. R. Drinkwater, J. P. Crawford, R. Bindschadler and R. Kwok, 1993, "Analysis of synthetic aperture radar data collected over the southwestern Greenland Ice Sheet", *Journal of Glaciology*, **39**(131), 115-132.
- Jezek, K. C., S. P. Gogineni and M. Shanableh, 1994, "Radar measurements of melt zones on the Greenland ice sheet", *Geophys. Res. Lett.*, **21**(1), 33-36.
- Munk, J., K. Jezek, F. Baumgartner, S. P. Gogineni, R. R. Forster and I. H. H. Zabel, 2000a, "Estimating a volumetric backscatter coefficient from in-situ measurements on the Greenland Ice Sheet", *IGARSS 2000*, Honolulu, Hawaii.
- Munk, J., K. Jezek, R. R. Forster and S. P. Gogineni, 2000b, "An accumulation map of the Greenland dry-snow zone derived from spaceborne radar", for *JGR*, Special PARCA Issue.

- Roman, D. R., B. Csatho, K. C. Jezek, and 4 others, 1997, "A comparison of Geoid Undulation Models for West-Central Greenland", *Jour. Geophys. Res.*, **102**(B2), 2807-2814.
- Shi, J. C., R. E. Davis, and J. Dozier, 1993, "Stereological determination of dry-snow parameters for discrete-scatterer microwave modeling", *Annals of Glaciology*, **17**, 295-299.
- Sohn, H. S., K. C. Jezek, and C. J. van der Veen, 1998, "Jakobshavn Glacier, West Greenland: 30 years of Spaceborne Observations", *Geophysical Research Letters*, **25**(14), 2699-2702.
- Sohn, H. G., and K. C. Jezek, 1999, "Mapping ice sheet margins from ERS-1 SAR and SPOT Imagery", *Journ. Rem. Sensing*, **20**(15-16), 3201-3216.
- Zabel, I. I. H., K. C. Jezek, P. A. Baggeroer and S. P. Gogineni, 1995, "Ground-based radar observations of snow stratigraphy and melt processes in the percolation facies of the Greenland ice sheet", *Annals of Glaciology*, **21**, 40-44.

3.2 Thesis and Dissertations

- Baggeroer, P. A., 1994, *Geoscience Data Management System: Design, Implementation and Analysis*, Master's Thesis, The Ohio State University, 110 p.
- Joshi, M., 1999, *Estimation of Surface Melt and Absorbed Radiation on the Greenland Ice Sheet Using Passive Microwave Data*, Ph.D. Dissertation, The Ohio State University, 158 p.
- Lampkin, D. J., 2000, *Investigation of Regional Basal Topography from Airborne Derived Surface Elevation and Improved Ice Thickness Models Over the Jakobshavn Drainage Basin*, Master's Thesis, The Ohio State University, 83 p.
- Roman, D. R., 1999, *An Integrated Geophysical Investigation of Greenland's Tectonic History*, Ph.D. Dissertation, The Ohio State University, 270 p.
- Sohn, H. G., 1996, *Boundary Detection Using Multisensor Imagery: Application to Ice Sheet Margin Detection*, Ph.D. Dissertation, The Ohio State University, 187p.
- Wilson, J.D., 1993, *Mapping a Fast Moving Glacier with Airborne Laser Altimetry*, Master's Thesis, The Ohio State University, 103 p.

4 References

- Baumgartner F., K. Jezek, R. R. Forster, S. P. Gogineni, and I. H. H. Zabel, 1998, "Spectral and angular ground-based radar backscatter measurements of Greenland snow facies", *IGARSS' 99*, Hamburg, Germany, 1052-1055.
- Bolzan, J.F, and K.C. Jezek, "Accumulation Rate Changes in Central Greenland from Passive Microwave Data", in revision, *JGR -Oceans*.
- Chang, A., Gloersen, P., Schmugge, T., Wilheit, T., and Zwally, H. J., 1976, "Microwave emission from snow and glacier ice", *Journal of Glaciology*, **16**(74), 23-29.
- Clark, T. and K. Echelmeyer, 1989, "High resolution seismic reflection profiles across Jakobshavns Ice Stream, Greenland", *EOS*, **70**(43), 1080. [Abstract.]
- Comiso, J. C., Zwally, H. J., and Saba, J. L., 1981, "Radiative transfer modeling of microwave emission and dependence on firm properties", *Annals of Glaciology*, **3**, 54-58.
- Fahnestock, M., Bindschadler, R., Kwok, R., and Jezek, K., 1993, "Greenland ice sheet surface properties and ice dynamics from ERS-1 SAR imagery", *Science*, **262**, 1530-1534.
- Forster, R. R., K. Jezek, J. Bolzan, F. Baumgartner, and S. P. Gogineni, 1999, "Relationships between radar backscatter and accumulation rates on the Greenland ice sheet", *International Journal of Remote Sensing*, **20**(15), 3131-3147.
- Jezek, K. C., S. P. Gogineni and M. Shanableh, 1994, "Radar measurements of melt zones on the Greenland ice sheet", *Geophys. Res. Lett.*, **21**(1), 33-36.
- Jezek, K. C., and S. P. Gogineni, 1992, Microwave Remote Sensing of the Greenland Ice Sheet, *IEEE Geosci. & Rem. Sens. Soc. Newsletter*, **9**, 6-10.
- Joshi, M., 1999, *Estimation of Surface Melt and Absorbed Radiation on the Greenland Ice Sheet Using Passive Microwave Data*, Ph.D. Dissertation, The Ohio State University, 158 p.

- Lampkin, D. J., 2000, *Investigation of Regional Basal Topography from Airborne Derived Surface Elevation and Improved Ice Thickness Models Over the Jakobshavn Drainage Basin*, Master's Thesis, The Ohio State University, 83 p.
- Munk, J., K. Jezek, F. Baumgartner, S. P. Gogineni, R. R. Forster and I. H. H. Zabel, 2000a, "Estimating a volumetric backscatter coefficient from in-situ measurements on the Greenland Ice Sheet", *IGARSS 2000*, Honolulu, Hawaii.
- Munk, J., K. Jezek, R. R. Forster and S. P. Gogineni, 2000b, "An accumulation map of the Greenland dry-snow zone derived from spaceborne radar", for *JGR*, Special PARCA Issue.
- Reeh, N., 1989, "Parameterization of melt rate and surface temperature on the Greenland Ice Sheet", *Polarforschung*, **59**, 113-128.
- Sohn, H. S., K. C. Jezek, and C. J. van der Veen, 1998, "Jakobshavn Glacier, West Greenland: 30 years of Spaceborne Observations", *Geophysical Research Letters*, **25**(14), 2699-2702.
- Zwally, H. J., 1977, "Microwave emissivity and accumulation rate of polar firn", *Journal of Glaciology*, **18**(79), 195-215.